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Editorial

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Towards a Consistent Approach for the Assessment and Redesign of Surface Water Quality Monitoring Networks

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Introduction

Water resources management in general, and water quality management in particular, requires both knowledge and a full understanding of the processes affecting water quantity and quality. A properly established water quality monitoring program is the only way in which one can understand various processes affecting water quality. It also provides managers and decision makers with the necessary information for effective and sustainable water quality management. Water quality monitoring programs consist of various activities, which include the designation of the monitoring objectives/purposes and the desired information, the design of the monitoring network and the sampling protocol, identification of the necessary laboratory analysis, a plan for data verification and storage, and the design of a data analysis protocol through which the desired information will be obtained. To ensure the utility of the generated data, the sampling processes, sample handling, and storage and laboratory analysis must be performed by professional staff. This is why the design of monitoring networks has generally been the activity that has received the most attention of researchers over the course of the last few decades [1-3]. However, as it stands now, there is no widely accepted established strategy or methodology for designing monitoring networks [2-3]. A logical and consistent design methodology that allows for more efficient and effective data collection and, consequently, more useful outputs, is critically needed. Such an approach would allow not only improved water pollution control recommendations and better allocation of financial resources, but also a better understanding of the ecosystem being monitored [3].

The initial step in the establishment of any monitoring program is to precisely define the monitoring objectives upon which the design of the monitoring network is based. The objectives should precisely indicate why we would do a sample at this specific site, what we want to measure, what is the type of information required, and what is the analysis tool that we intend to use in order to obtain the desired information. Monitoring objectives should be identified in cooperation with different stakeholders such as policy makers, water managers, researchers and the public. A literature review reveals that the most stated water quality monitoring objectives are [3-5] to assess spatial and temporal trends in water quality; to assess compliance with established water quality standards; to assess the effects of natural and anthropogenic factors on the general trends in water quality processes; to determine suitability for various water uses; to assess the effectiveness of water pollution control measures; to assess the general water quality conditions over a wide area; and to facilitate impact assessment studies, mass transport and water quality modeling, as well as other specific research activities. However, it should be emphasised that climate change impacts on surface water quality have not been addressed to date as a water quality monitoring objective [3].

The assessment and redesign of water quality monitoring networks is not a straightforward process, and is based mainly on the monitoring objectives. Therefore, it is very important that the monitoring objectives be carefully and precisely defined. Identification of the monitoring objectives should be specific, clearly stated, and preferably on a site-by-site basis [3]. The monitoring network design consists of three main aspects: where to measure (sampling sites), what to measure (water quality variables), and how frequently to measure (sampling frequency). Given that water quality is a complex topic, statistical approaches can make a significant contribution regarding the assessment of the performance of a monitoring network [3]. Research into the assessment of the main components of water quality monitoring networks has been ongoing since the 1970s [1,6-16].

In the following sections, statistical approaches that have been used to date for the assessment and redesign of each of the monitoring network components, as well as combined assessments, are summarized. Advantages and disadvantages from the design point of view and recommendations for further work are also presented.

Sampling Sites

The approaches that have been proposed to date for the assessment of the spatial distribution of the sampling sites have several deficiencies. Some approaches employ only one water-quality variable, even though reliable assessments should be based on a number of water quality variables simultaneously and not sequentially (e.g. stream order approach proposed by Horton [17], Sharp [6,7], Sanders et al. [9]; regression analysis proposed by Tirsch and Male [10], entropy concept proposed by Harmancioglu and Alpaslan [12]). Some approaches are based mainly on the assumption of a linear structure in the data (e.g. regression analysis proposed by Tirsch and Male [10]; entropy concept proposed by Harmancioglu and Alpaslan [12]; multivariate data analysis approaches proposed by Odom [13], Ouyang [14], and Khalil et al. [16]). As well, some of the approaches do not consider reconstruction of information about discontinued sites (e.g. stream order approach proposed by Horton [17]; entropy concept proposed by Harmancioglu and Alpaslan [12]; multivariate data analysis approaches proposed by Odom [13], and Ouyang [14]).

In addition, the approaches that have been proposed to date focus mainly on identifying sampling sites to be discontinued. However, the optimum spatial distribution of sampling sites may involve discontinuing a number of existing sites, while including some of the ungauged sites. This main point was considered by Khalil et al. [16] by incorporating basin characteristics in the assessment approach, and employing cluster analysis and an information index to identify the optimal combination of sites to discontinue, sites to be continuously

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measured, and sites to be added. New technologies and techniques need to be explored with respect to the assessment of the spatial distribution of sampling sites. For example, the main advantage of using multivariate data analysis is that it allows for the use of several water quality variables in the assessment procedure simultaneously. However, it relies on the linear structure of the data used. This could be potentially improved through the use of a new generation of nonlinear multivariate data analysis methods (Nonlinear PCA (NLPCA) and Nonlinear Canonical Correlation Analysis (NLCCA) [18]).

Water Quality Variables

Two main statistical techniques have been proposed to date for the assessment of water quality variables: the correlation regression (CR) approach [1,9] and Principal Component Analysis (PCA) [14]. The advantage of the CR approach is that it allows for the reconstitution of information about discontinued variables. In addition, the modified version of the CR approach, proposed by Khalil et al. [15], overcomes two main deficiencies in the CR approach. Khalil et al. [15] proposed a correlation coefficient threshold above which the variables can be considered highly correlated, and an information index that allows for the identification of the optimal combination of variables to be continuously measured, as well as variables to be discontinued.

These approaches (the CR, its modified version proposed by Khalil et al. [15], and PCA) are mainly based on the assumption of a linear relationship among water quality variables. However, the relationship between physical, biological and chemical variables may be nonlinear. Thus, mutual information and nonlinear regression or artificial neural networks (ANN) may be used instead of linear correlation and regression analysis. Mutual information is a measure of a nonlinear dependence or the amount of redundant information between two variables [19,20]. ANNs are more flexible than regression models in their ability to capture the relationships among water quality variables, and they require less prior knowledge of the system under study [21]. However, ANNs are recommended for the substitution of individual missing values, but not as a record extension technique [22]. ANN as a record extension technique has two main deficiencies: it provides extended records with an underestimated variance, and it is sensitive to the presence of outliers [22]. Thus, a nonlinear record extension technique that can maintain the variance of the extended records, and which is sensitive to the presence of outliers, is required.

Sampling Frequency

The approaches proposed for the assessment of sampling frequency are based mainly on the monitoring objectives. These approaches address a specific water quality variable at a particular sampling site, and often result in the optimization of sampling frequency based on only one of the monitoring objectives. For instance, Lettenmaier [23] proposed a sampling approach to determine the optimum sampling frequency for trend detection. Sanders and Adrian [8] proposed the confidence interval about the mean as a criterion for the assessment of ambient water quality. Zhou [24] proposed an approach aimed at defining the sampling frequency in terms of periodicity based on harmonic analysis. Mace [25] and Ward et al. [26] described an approach for sampling frequency assessment in order to control the risk of type I and type II errors for compliance with standards assessment. In addition, Tirsch and Male [10] addressed the temporal design of networks using multivariate linear regression, Harmancioglu [11] introduced the entropy concept as a way to determine the optimal sampling intervals, and Khalil et al. [27] proposed the semivariogram to assess sampling frequency based on the range of autocorrelation.

Assessment of sampling frequency by statistical methods often results in the optimization of sampling around one of the monitoring objectives [26]. Water quality monitoring cannot address every information need through one data collection procedure [4]. However, the monitoring network must attempt to meet several objectives simultaneously [3]. Several suggestions to overcome this challenge have been proposed. Whitfield [4] suggested that different sampling frequencies should be used for different monitoring objectives in order to maximize the information gain. Zhou [24] assessed different sampling frequencies for different monitoring objectives, and selected the highest sampling frequency in order to fulfill multiple objectives.

In addition, statistical approaches are used to assess the sampling frequency of a specific water quality variable at a particular sampling site. However, in practice, water quality monitoring networks usually measure several variables at several sites. Ward [28] and Sanders et al. [9] suggested proportional sampling to address this issue. Proportional sampling may be used to distribute a pre-identified total number of samples among sampling sites and/or variables. However, using proportional sampling may provide a number of samples that may not satisfy all the objectives at all the sites for all of the measured variables. Thus, the consequences of applying proportional sampling should be evaluated. The assessment of the sampling frequency for different objectives simultaneously is a possible area for further research.

Combined Assessment

Although many studies have sought to improve the performance of monitoring networks, most have mainly focused on only one aspect of network design. Few researchers have examined the optimization of different aspects simultaneously [10, 12]. Network assessment and redesign requires combining the assessment of the variables to measure, sampling frequency and sampling sites into one framework. The three main aspects in monitoring design should be assessed simultaneously, and may be linked by a criterion of either cost or information. These assessments can also serve to resolve the trade-off between the number of water quality variables measured and their sampling frequency and sites. Thus, the decision will be either to discontinue more variables in favor of keeping more sampling sites and/or increasing the sampling frequency, or to keep more variables, while decreasing the number of sites and/or the frequency.

Conclusions

This editorial highlights the main statistical approaches that have been proposed for the assessment and redesign of each of the main components of water quality monitoring networks (sampling sites, water quality variables and sampling frequency). It should be emphasized that monitoring network objective statements should precisely indicate the following important points: why we would do a sample at each site, what we want to measure, what is the type of information required, and what is the analysis tool that we intend to use in order to obtain the desired information? As was mentioned earlier, climate change impacts on surface water quality have not been addressed to date as a water quality monitoring objective; this warrants study in the future.

Recommendations for further research were also highlighted in this editorial for each of the main components of a monitoring network, and can be summarized as follows:

- Assessment and redesign of sampling sites should aim to identify not only the optimal combinations of sites to discontinue, and sites to be continuously measured, but also sites to be added.

- The use of the recently developed nonlinear multivariate data analyses techniques (e.g. Nonlinear PCA and Nonlinear CCA) should be explored for the assessment and redesign of sampling sites.
- A nonlinear record extension technique that can maintain the variance of the extended records, and which is sensitive to the presence of outliers, is required.
- The assessment of the sampling frequency for different objectives simultaneously is a potentially useful area for further research.
- The consequences of applying proportional sampling for several water quality variables at several sampling sites should be evaluated.
- Simultaneous combined assessment of the three main components of water quality monitoring networks (sampling sites, water quality variables and sampling frequency) using an information or a cost criterion is required.

Finally, the design of a monitoring network needs to be periodically re-assessed and modified accordingly due to shifts in management priorities and/or changing environmental conditions.

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